NASA TN D-269

7N-26
198728
P-37

# TECHNICAL NOTE

## D-269

### INITIAL INVESTIGATION OF ARC MELTING AND EXTRUSION OF TUNGSTEN

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON March 1960

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## SUMMARY

Tungsten was vacuum arc-cast into ingots $1\frac{1}{2}$ inches in diameter and up to 9 inches long using direct-current reverse polarity. Similar attempts to melt the electrode with direct-current straight polarity produced no appreciable melting. Little further purification of the high-purity (99.95 percent) tungsten electrode was obtained during melting, presumably because the rapid melting rate allowed too little time for volatilization of impurities.

Extrusion appears to be a very promising method for the initial breakdown of the large as-cast tungsten grains. Clad tungsten billets were successfully extruded at 2300° and 3100° F at reduction ratios up to 8:1 by conventional low-velocity procedures using a lubricant. Using similar low-velocity extrusion procedures, unclad tungsten could not be extruded at a reduction ratio of 6:1, temperatures up to 3600° F, and a press pressure of 150,000 pounds per square inch. Unclad tungsten was extruded by a high-velocity extrusion process at temperatures between 3000° and 3800° F with reduction ratios up to 45:1 without the use of a lubricant. Hot-working was observed in some of these high-velocity extrusions.

Tensile tests at 1000° F on arc-melted tungsten extruded at low velocities yielded ultimate strengths similar to those of low-velocity extruded, sintered tungsten and commercially sintered and swaged bar stock. The ultimate strength and hardness values of the high-velocity extruded material were much lower than those of the materials produced by other processes studied.

## INTRODUCTION

Tungsten, because of its high melting point (6170° F) and high strength at elevated temperatures, is currently being considered for use as a structural material in advanced nuclear reactors, high-velocity missiles, and space vehicles. Commercially produced tungsten, up to the present time, has been fabricated by powder metallurgical techniques. Recently there has been a desire to produce larger, more uniformly dense tungsten bodies with higher purity and greater ductility than are ordinarily obtained by powder metallurgy methods. This has led to the investigation of vacuum arc-casting as a method of producing tungsten.

The present investigation summarizes the results of a preliminary study of arc-melting and subsequent fabrication of tungsten conducted at the NASA Lewis Research Center. These subjects have also been investigated by others (refs. 1 to 3).

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The purposes of this study were to investigate arc-melting as a method for producing dense tungsten ingots, to study extrusion as a method for breaking up the coarse grain structure of the arc-cast ingots, and to evaluate certain mechanical properties of arc-cast and extruded tungsten. In this study, tungsten ingots were vacuum arc-cast using direct-current reverse polarity. Billets prepared from these ingots were extruded at both conventional low-velocity extrusion rates and high-velocity extrusion rates using the "Dynapak" process (ref. 4). For comparison, tungsten billets prepared by powder metallurgy techniques and vacuum-arc-cast ingots commercially produced with alternating current were also extruded under similar conditions. Tensile tests of sections of the extruded bars were conducted in order to compare the mechanical properties of the worked arc-cast and worked sintered tungsten.

## MATERIALS

### Arc-Casting

The arc-cast ingots produced at this laboratory were made by consumably arc-melting 3/4-inch-diameter electrodes of commercially pure sintered and swaged tungsten rod. An analysis of typical electrode material is given in table I.

### Extrusion

For the low-velocity extrusion studies, ten tungsten billets were used; seven were vacuum arc-cast and three were hydrogen sintered. Of the seven vacuum-arc-cast billets, five were produced at the NASA Lewis Research Center using direct-current techniques which are described in detail in this report and two were melted by the Climax Molybdenum Company of Michigan using alternating-current methods. The three hydrogen-sintered billets were prepared by the Lamp Wire and Phosphors Department of The General Electric Company. Most of the arc-cast ingots were machined to remove surface defects. The general appearance of arc-cast and sintered billets is compared in figure 1. Chemical analyses of representative samples of these billets after extrusion are also reported in table I.

For the high-velocity extrusion studies, 11 tungsten billets were used. All were prepared at the Lewis Research Center. Six of these billets were hydrostatically pressed, presintered in hydrogen, and sintered in vacuum. The other five billets were vacuum arc-cast using subsequently described procedures.



Summaries of the types of materials used as well as the extrusion conditions are given in tables II and III.

## APPARATUS AND PROCEDURE

### Arc-Melting



The arc-melting studies were conducted in the arc furnace shown in figures 2 and 3. The main components of the vacuum pumping system for this furnace include a 6-inch oil diffusion pump, a 6-inch oil booster pump in parallel with the diffusion pump, and a 100-cubic-foot-per-minute mechanical forepump. For this investigation, the oil booster pump was used in preference to the diffusion pump because the latter could not handle the gas load during the melting process. The booster pump could usually maintain an operating pressure of about 5 microns ($5\times10^{-3}$ mm Hg). This pressure, however, was read on a vacuum gage located in the vacuum piping immediately adjacent to the melting chamber. The pressure at the surface of the melt was, of course, greater.

The arc length during melting was maintained by a semiautomatic voltage controller; however, it was necessary to select manually an electrode feed rate in the range 0 to 21 inches per minute. This feed rate could be varied manually during the melting cycle. The ideal feed rate is that required to maintain a constant arc length. If this condition is met, the voltage controller will continually call for power; however, if this speed is exceeded, the controller will cut off and on as required to maintain the arc. If set too high, the electrode will hunt a stable position and cause poor voltage control. Power was supplied to the furnace from three 1540-ampere direct-current rectifiers with a maximum open-circuit voltage of 78 volts.

Melting was attempted using both straight (electrode negative) and reverse (electrode positive) polarity. Attempts were made to melt

3/4-inch-diameter swaged tungsten electrodes into a $1\frac{1}{2}$-inch-diameter water-cooled copper mold with a removable water-cooled copper stool (base). Initial melting attempts were made with straight polarity using currents ranging up to 4500 amperes and voltages varying to a maximum of 38 volts. Later attempts to melt with reverse polarity required similar current settings with smaller voltages.



## Extrusion

The extrusion of arc-cast tungsten, based on the results obtained with molybdenum (ref. 5), appears to be one of the most desirable methods for the initial breakdown of the large as-cast grains. Since extrusion equipment was not available at the Lewis Research Center, extrusion attempts were made by industrial organizations. Details of the equipment used are listed in the following table:

| Extrusion source | Type of press | Diameter of billets, in. | Maximum speed of press, in./min | Method of heating billet |
|---|---|---|---|---|
| Nuclear Metals, Inc. | 1000-ton horizontal | 3 | 145 | Air atmosphere, Globar furnace |
| Tapco Group, Thompson Ramo Wooldridge, Inc. | 150-ton vertical | 1.52 | 94 | Inert atmosphere, induction furnace |
| Dynapak Convair Division, General Dynamics Corporation | 160,000-ft-lb high velocity, rate dependent | 1 | 150,000 | Inert atmosphere, induction furnace |

The low-velocity extrusion studies utilized standard extrusion procedures except as noted in the next paragraphs.

Two vacuum-arc-cast billets (A1 and A2, table II) and the three sintered billets (S1 to S3, table II) were clad in type 304 stainless steel. These jackets served to protect the billets from oxidation during the heating cycle and in addition increased the diameter of the billet to that of the die container. After being heated in a Globar furnace to 2300° F, these compacts were coextruded with powdered glass as a lubricant.

Vacuum-arc-cast billets (A3 to A5, table II) were canned in columbium to be built up to the required die container size. These billets were then heated inductively in an argon atmosphere to 3100° F and extruded with a combination of graphite and powdered glass as a lubricant.

In order to avoid the necessity for cladding, two attempts were made to extrude unclad as-cast tungsten (A6 and A7, table II). It should be noted that the surface of these billets was rough because there was not sufficient stock to clean the arc-cast billet and still have the billet fit the container. To compensate for the increased friction due to the rough tungsten surface, the extrusion temperatures were raised to 3200° and 3600° F. These billets were also heated inductively in an argon atmosphere.



The high-velocity extrusion process is unique in many ways. It utilizes a pneumatically energized metalworking machine that develops high velocities (up to 150,000 in./min) at high energy levels (up to 160,000 ft-lb). In view of the capabilities of this equipment, attempts were made to extrude tungsten at much higher reduction ratios than had been attempted in previous studies.

The billets used in this section of the study were heated inductively in direct line with the extrusion ram. Both the induction coil and the billet were completely encased in an argon-filled plastic bag during the heating cycle. When the billets reached the extrusion temperature, the power and cooling water to the induction coil were shut off, and the ram was released. The latter action forced the billets into the container and through the die in one continuous motion. No lubricant was used in any of these extrusions.

The $K$ values listed in table II were calculated from the following formula (ref. 6):

$$K = \frac{P}{\ln(R)}$$

where

$K$ extrusion constant

$P$ maximum pressure on billet

$R$ reduction ratio

The value of $K$ is an experimentally determined temperature-dependent constant. Once obtained for a set of conditions, it is useful as an approximation of the pressure required to extrude a metal at any reduction ratio under these given conditions. The values reported for $K$ in table II are rough guides for the relative ease of extrusion of tungsten; however, all comparisons drawn are only approximations, since such factors as press speed, lubrication, die angle, and so forth, are not considered in the formula.

### Tensile Testing

Two different series of tensile tests were conducted on samples machined from extrusion products in an attempt to determine the effect of varying extrusion conditions on certain mechanical properties. The series of relatively low temperature (700° and 1000° F) tensile tests was conducted in an argon atmosphere using standard tensile testing procedures. Total elongation and yield strength were determined through use of an extensometer. The high-temperature (4000° F) tensile tests were conducted in a vacuum using the apparatus and procedures described in reference 7. For comparison, similar tests were conducted on commercially sintered and swaged bar stock.

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## RESULTS AND DISCUSSION

### Arc-Melting

Arc melting with straight polarity. - Initial attempts to melt tungsten were made using direct-current straight polarity (electrode negative). In these trials, 3/4-inch-diameter swaged tungsten electrodes were used with currents ranging from 1500 to 4500 amperes at 22 to 38 volts in a $1\frac{1}{2}$-inch-diameter mold. All such attempts to produce a tungsten ingot using straight polarity were unsuccessful. The electrode did not melt, and the arc frequently penetrated the water-cooled copper mold stool. Failures of the copper stool were eliminated by use of a thick tungsten cover plate on the stool, but no appreciable consumption of the electrode was achieved. Reference 1 reports that larger (4-in. diam.) ingots were successfully melted using straight polarity; however, these investigators also encountered difficulties when attempting to melt smaller diameter ingots by the same method (personal communication).

Arc-melting with reverse polarity. - It has been shown (ref. 8) that in melting with a direct-current arc the heat is distributed unevenly between the anode and the cathode. With the refractory metals molybdenum and tungsten, most of the heat is concentrated at the anode (i.e., the copper mold with straight polarity). In order to increase the electrode melting rate, the polarity was reversed and the electrode was made positive. This modification was immediately successful. With a current of 3400 amperes at 23 volts, the 3/4-inch-diameter electrode melted at the very rapid rate of approximately 5 pounds per minute. It was then necessary to feed the electrode very rapidly (about 17 in./min) so that the arc did not become too long and wander to the mold wall. When the distance from the melt to the electrode exceeded the distance from the electrode to the mold wall, the arc was apt to jump to the mold wall. To decrease the melting rate, the arc power was reduced. This caused insufficient heat to be supplied to the molten pool, and an unsound spongy ingot resulted. By interposing a 0.005-inch-thick tungsten liner in the copper mold in order to slow down the rate of heat transfer to the mold wall and keep a larger pool of molten tungsten, the porosity was restricted to a surface layer about 1/8 inch deep on the resulting ingots. This procedure produced acceptable ingots $1\frac{1}{2}$ inches in diameter and up to 9 inches long by melting 3/4-inch-diameter swaged electrodes with an arc current of 3500 to 4500 amperes at 22 to 25 volts. A typical as-cast tungsten ingot and a machined ingot are compared in figure 4. These ingots cleaned up very well to a final diameter of about $1\frac{1}{4}$ inches, and very little piping was encountered. The small amount of piping that was found was easily removed by cropping.

Chemical analyses of the typical tungsten specimens are given in table I. A comparison of the impurity content in the ingots with that of the high-purity electrodes indicates that little, if any, additional purification of oxygen, nitrogen, carbon, iron, and molybdenum was achieved by this arc-melting process.

The high melting rate encountered in melting tungsten with direct-current reverse polarity probably limits the purification that can be achieved, since little time is available for volatilization of impurities from the electrode and molten pool. In this respect the lower melting rate reported (ref. 1) with direct-current straight polarity may be advantageous because it permits considerably more time for the vacuum to act on the electrode and molten pool. As mentioned before, however, reversed polarity apparently has the advantage of permitting the melting of smaller diameter ingots. The rapid melting rate of reversed polarity would also be advantageous for alloy melting, since it would permit less time for volatilization of alloy additions.

## Extrusion

An undesirable characteristic of arc-cast tungsten is the very coarse columnar grain structure of the ingots (fig. 5). Since embrittling impurities such as oxides tend to concentrate in the grain boundaries, their concentration in the grain boundaries of a coarse-grained ingot is much higher than it would be in a fine-grained specimen of the same purity. Extrusion has been used very successfully for breaking down the coarse grain structure of arc-cast molybdenum and was therefore investigated for the initial working of arc-cast tungsten.

Low-velocity extrusion at 2300° F. - Two of the stainless-steel-clad sintered tungsten billets (S1 and S2, table II) were successfully extruded at speeds of 70 and 145 inches per minute and reduction ratios of 4:1 and 5.35:1, respectively. The third sintered billet (S3) stalled the press when a reduction ratio of 5.5:1 was attempted. The two stainless-steel-clad arc-cast billets were successfully extruded at a reduction ratio of 5.5:1 and a speed of 70 inches per minute. Other pertinent extrusion data are listed in table II. E-566

The arc-cast and sintered bars in the as-extruded condition and with the cladding mechanically removed are shown in figures 6 and 7, respectively. The surfaces of the sintered bars were much smoother but the diameters of these extrusions varied more than those of the arc-cast extrusions. The rough surfaces of the arc-cast bars were caused by extrusion of the large tungsten grains into the relatively soft stainless steel. Radiographs of the as-extruded bars indicated the bars were sound with only a few small cracks in the leading ends. Hardness data for representative billets and extrusions are given in table IV. The grain refinement in the transverse direction of an arc-cast billet extruded under a 5.5:1 reduction ratio is shown in figure 8, while figure 9 illustrates the cross-sectional grain refinement of a sintered billet and the removal of initial porosity resulting from extrusion at a 5.35:1 reduction ratio. These grains were elongated in the longitudinal direction. Since there were no signs of recrystallization and the hardness increased considerably, these billets were evidently cold-worked.

Although the extrusions just described were satisfactory from the standpoint of soundness and grain refinement, several difficulties were apparent. A temperature of 2300° F limited the extrusions to relatively low extrusion ratios in order not to exceed the capacity of the press. In addition, the stainless steel cladding used to prevent oxidation during heating appeared undesirable. At the extrusion temperature of 2300° F, the stainless steel cladding was much softer than the tungsten core. Thus, during the initial extrusion breakthrough, the soft stainless steel extruded readily with little corresponding reduction of the tungsten. As the extrusion proceeded, however, the buildup of the stainless steel caused coextrusion of the core and cladding. This resulted in the diameter variation or "dog-bone" effect shown in figure 7.

Low-velocity extrusions at higher temperatures. - In order to overcome the limitations mentioned in the last section, extrusions were attempted at higher temperatures (up to 3600° F). The columbium-canned arc-cast billets (A3 to A5) were successfully extruded at 3100° F at reduction ratios of 5.5:1 and 8:1. Data on the materials and extrusion conditions used are summarized in table II.

Radiographs of the extruded billets indicated that these extrusions were as sound as those produced at lower temperatures. A portion of a typical columbium-clad extrusion is shown in figure 10. The considerable transverse grain refinement resulting from the 5.5:1 reduction at 3100° F is shown in figure 11.



Two unclad tungsten billets, A6 and A7, were heated to 3200° and 3600° F, respectively; however, both attempts to extrude were unsuccessful at a press pressure of 150,000 pounds per square inch. The columbium-clad billets had extruded completely with a pressure of 110,000 pounds per square inch. Both unclad billets were then machined, columbium clad, and successfully extruded at 3200° F using the same lubricant (billets A6A and A7A, table II). From these results it appears that the columbium jacket acts as an additional lubricant between the steel die and the tungsten billet during extrusion.



Examination of the microstructure of all the low-velocity extruded bars revealed that only cold-worked structures resulted. There were no recrystallized grains (indicative of hot-working), even in bars extruded at the highest temperature (3200° F), the maximum reduction ratio (8:1), and the most rapid extrusion speed (94 in./min).

High-velocity extrusions. - During the time that the low-velocity extrusion studies were being conducted, a new high-velocity extrusion process was introduced. Since this new process appeared to have possibilities of attaining much higher reduction ratios, arrangements were made to have 11 billets extruded. Studies were conducted over a temperature range of 3000° to 3800° F at reduction ratios up to 45:1. All five of the arc-cast billets and four of the six vacuum-sintered billets extruded successfully. Lubricants were not used. Details of this series of extrusions are listed in table III. Although these data indicate that arc-cast tungsten extruded more successfully than sintered tungsten, the extruder reported no difference in ease of extrusion.

Photographs of some of the starting billets, dies, and extruded products of this high-velocity extrusion process are shown in figures 12 to 14. Most of the extruded bars had relatively clean, uniform surfaces. Some of the longer extrusions had twisted ends as a result of having struck a stopping plate while still traveling at high velocities. Other extrusions exhibited necked regions as a result of continued momentum at the end of ram travel (see figs. 13 and 14).

The microstructure of a high-velocity extruded arc-cast billet (reduction ratio, 45:1; extrusion temperature, 3800° F) taken in a longitudinal plane is shown in figure 15. The fact that the grains are equiaxed in this plane indicates that the extrusion was completely recrystallized. Apparently true hot-working of tungsten has been obtained under these conditions. For the extrusions at lower temperatures and lower reduction ratios, varying degrees of recrystallization were noted. Even at the lowest temperature (3000° F) and lowest reduction ratio (7.4:1) attempted in the high-velocity extrusions, partial recrystallization was obtained, as illustrated in figure 16.



## Tensile Testing

Since insufficient extruded material was available to permit a study of the tensile properties as a function of temperature, a test temperature of 1000° F was selected for most of the tests. This temperature was selected as a convenient one above the usual ductile-to-brittle transition temperature range for tungsten. The results of tensile tests of the extruded material are presented in table V.

On the basis of ultimate tensile strengths, all the low-velocity extrusions were quite similar. All but one of the low-velocity extruded specimens exhibited a ductile type fracture (specimen necked) at 1000° F. The single exception was a specimen of the alternating-current vacuum-arc-melted and extruded tungsten. In addition to showing a brittle type fracture, this specimen exhibited only 10-percent elongation at fracture. The single available tensile specimen of sintered and extruded material showed the most ductility (i.e., an elongation of 47 percent at the 1000° F test temperature).

Although all the direct-current arc-cast low-velocity extruded material exhibited a ductile fracture at 1000° F, another specimen of the same material (billet A4) exhibited a brittle fracture at 700° F. It may be that this temperature was below the ductile-to-brittle transition temperature for this material worked under these particular conditions. Unfortunately, enough of this material was not available to pinpoint the transition temperature more accurately.

As previously mentioned, 9 of 11 high-velocity extrusions were successful, but only enough straight material was obtained from these products to tensile test three bars successfully (billets SD1, SD5, and AD3, table V). The ultimate tensile strengths for the three tests were similar, but the values were much lower than those of the low-velocity extruded material. The hardness values (table IV) were also lower than for low-velocity extruded tungsten. These results are to be expected, since the high-velocity extruded material contained less evidence of cold-working than the low-velocity extrusions. The arc-cast high-velocity extruded tungsten (two specimens from two billets) was much more ductile than the vacuum-sintered material (one specimen available) which exhibited a brittle fracture. Data at 1000° F are also shown for commercially sintered and swaged rod (containing effects of cold-working). The strength of the low-velocity extruded material was comparable with that of the swaged rod, while the strength of the high-velocity extruded material was less.

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Previous investigation of commercially sintered tungsten (ref. 9) indicated that, at temperatures above 3200° F, this material fractures in a brittle fashion (with no necking). To investigate whether the extruded arc-cast material would exhibit the same behavior, a single specimen was tested at 4000° F. The tensile properties of this specimen (A6A) are compared in table V with data from reference 9 for commercially sintered and swaged tungsten. Fractured specimens are compared in figure 17. The greater ductility of the arc-cast material at 4000° F is evidenced by the types of fractures shown in the figure. Table V also shows a greater reduction in area and increased elongation with very little loss in strength for the arc-cast extruded material over the values obtained with sintered and swaged commercial rod stock (ref. 9).

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## SUMMARY OF RESULTS

This preliminary investigation of the arc-melting and extrusion of tungsten provided the following results:

1. Ingots $1\frac{1}{2}$ inches in diameter and up to 9 inches long were produced by vacuum arc-melting using direct-current reverse polarity (electrode positive). Sound ingots were obtained by machining about 1/8 inch from the as-cast surface. In a typical melt, a 3/4-inch-diameter swaged tungsten electrode was consumably melted at a rate of approximately 5 pounds per minute in a vacuum of less than 10 microns ($10^{-2}$ mm of Hg) using 23 volts at 3400 amperes. At similar power levels attempts to melt the electrode using direct-current straight polarity produced no appreciable melting.

2. Very little further purification of the high-purity tungsten electrodes was obtained by vacuum arc-melting in this investigation, presumably because the melting rate was very rapid and thus allowed too little time for volatilization of impurities.

3. Extrusion appears to be a promising method for grain refinement of arc-cast tungsten. Although conventional low-velocity extrusion attempts with reduction ratios up to 5.5:1 were successful at 2300° F, extrusion at higher temperatures (i.e., above 3000° F) appears desirable.

4. Columbium-clad tungsten was readily extruded by a conventional low-velocity process at reduction ratios up to 8:1 at a temperature of 3100° F using a lubricant. Under similar conditions and with temperatures up to 3600° F, unclad tungsten could not be extruded at a reduction ratio of 6:1 at a press pressure of 150,000 pounds per square inch. No indications of a recrystallized structure were noted, even at an extrusion temperature of 3200° F with an extrusion ratio of 8:1.

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5. Using a high-velocity extrusion process (i.e., up to 150,000 in./min) unclad tungsten was successfully extruded with no lubricant at temperatures in the range 3000° to 3800° F with reduction ratios up to 45:1. A hot-worked structure was observed in a billet extruded at 3800° F with a reduction ratio of 45:1. Varying degrees of hot-working were observed in other high-velocity extrusions extruded at lower temperatures and extrusion ratios.

6. The results of tensile tests at 1000° F indicated only slight differences in the ultimate tensile strengths of tungsten (approximately 70,000 psi) produced by the following methods:

(a) Vacuum arc-cast and low-velocity extruded

(b) Sintered and low-velocity extruded

(c) Sintered and swaged (commercial rod stock)

The high-velocity extruded tungsten was softer and much lower in tensile strength at 1000° F than was the tungsten produced by the other processes.

7. A tensile test conducted in vacuum at 4000° F on a sample of low-velocity-extruded vacuum-arc-cast material indicated that this material was more ductile (with very little loss in strength) at this temperature than sintered and swaged commercial rod stock.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, December 16, 1959

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TABLE I. - CHEMICAL ANALYSES OF RANDOM ELECTRODES AND BILLETS

| Element | Sintered and swaged rod stock (starting electrode), parts/million | NASA vacuum-arc-cast ingot, parts/million | Commercial vacuum-arc-cast billet (as-extruded), parts/million | Commercial hydrogen-sintered billet (as-extruded), parts/million |
|---|---|---|---|---|
| Oxygen | 24 | 20 | 26 | 13 |
| Nitrogen | 18 | 18 | -- | -- |
| Carbon | 22 | 26 | 21 | 50 |
| Aluminum | <5 | <5 | <10 | <10 |
| Calcium | <10 | <10 | <50 | <50 |
| Chromium | <5 | <5 | <20 | <20 |
| Copper | <5 | <5 | <10 | <10 |
| Iron | 30 | 10 | 30 | 30 |
| Molybdenum | 50 | 50 | 100 | <50 |
| Nickel | <5 | <5 | <10 | <10 |
| Potassium | <10 | <10 | 14 | 21 |
| Silicon | <5 | <5 | 10 | 10 |
| Sodium | <10 | <10 | 17 | 25 |
| Tantalum | --- | --- | <100 | <100 |
| Thorium | <50 | <50 | <100 | <100 |

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TABLE II. - LOW-VELOCITY EXTRUSION DATA

| Billet | Size of unclad billet, | | Cladding material and thickness | Reduction ratio | Extrusion temperature, °F | Extrusion speed, in./min | Peak value of K, psi |
|---|---|---|---|---|---|---|---|
| | Diameter, in. | Length, in. | | | | | |
| Hydrogen-sintered billets | | | | | | | |
| S1 | $2\frac{1}{4}$ | $3\frac{1}{2}$ | 0.340-In. stainless steel | 4.0:1 | 2300 | 70 | 109,300 |
| S2 | ↓ | ↓ | ↓ | 5.35:1 | ↓ | 145 | 89,500 |
| S3 | ↓ | ↓ | ↓ | 5.5:1 | ↓ | Stalled 1000-ton press | ------- |
| Vacuum-arc-cast billets (melted with alternating current) | | | | | | | |
| A1 | $2\frac{1}{8}$ | $2\frac{3}{4}$ | 0.340-In. stainless steel | 5.5:1 | 2300 | 70 | 74,900 |
| A2 | $2\frac{1}{8}$ | $2\frac{3}{4}$ | 0.340-In. stainless steel | 5.5:1 | 2300 | 70 | 77,100 |
| Vacuum-arc-cast billets (melted with direct-current reverse polarity) | | | | | | | |
| A3 | $1\frac{3}{16}$ | $2\frac{1}{2}$ | 0.25-In. columbium | [a]5.5:1 | 3100 | 94 | 61,300 |
| A4 | ↓ | ↓ | ↓ | [a]5.5:1 | ↓ | ↓ | 59,400 |
| A5 | ↓ | ↓ | ↓ | 8.0:1 | ↓ | ↓ | 53,000 |
| A6 | $1\frac{1}{2}$ | 3 | None | [a]5.5:1 | 3200 | Stalled 150-ton press | ------- |
| A7 | $1\frac{1}{2}$ | 3 | None | 8.0:1 | 3600 | Stalled 150-ton press | ------- |
| [b]A6A | $1\frac{3}{8}$ | $2\frac{1}{2}$ | 0.060-In. columbium | [a]5.5:1 | 3200 | 94 | 66,500 |
| [c]A7A | $1\frac{3}{8}$ | $2\frac{1}{2}$ | 0.060-In. columbium | 8.0:1 | 3200 | 94 | 60,800 |

[a]Reduction ratio for dies used on these billets was actually 6:1, but "washed out" to 5.5:1 for most of extrusions. Value of K for these billets is based on initial breakthrough at 6:1 ratio.

[b]A6 columbium clad and repressed.

[c]A7 columbium clad and repressed.

TABLE III. - HIGH-VELOCITY EXTRUSION DATA

| Billet | Starting billet size | Reduction ratio | Extrusion temperature, °F | Dimensions of extruded product | |
|---|---|---|---|---|---|
| | | | | Cross section | Total length, in. |
| Vacuum-sintered billets | | | | | |
| SD1 | 1-In. diam. 1 In. long | 16:1 | 3500 | 0.250-In. diam. | 6 |
| SD2 | | 45:1 | 3800 | 0.150-In. diam. | Did not extrude |
| SD3 | | 8.3:1 | 3500 | 1/8 By 3/4 in. | Did not extrude |
| SD4 | | 16:1 | 3300 | 0.250-In. diam. | 3 |
| SD5 | | 9.5:1 | 3000 | 0.325-In. diam. | $2\frac{1}{2}$ |
| SD6 | | 35:1 | 3500 | 0.170-In. diam. | $1\frac{1}{4}$ |
| Vacuum-arc-cast billets (melted with direct-current reverse polarity) | | | | | |
| AD1 | 1 In. diam. 1 In. long | 45:1 | 3800 | 0.150-In. diam. | 8 |
| AD2 | | 7.4:1 | 3000 | 0.368-In. diam. | $5\frac{1}{4}$ |
| AD3 | | 16:1 | 3500 | 0.250-In. diam. | 9 |
| AD4 | | 8.3:1 | 3500 | 1/8 By 3/4 in. | $4\frac{3}{4}$ |
| AD5 | | 40:1 | 3800 | 0.158-In. diam. | 10 |

TABLE IV. - REPRESENTATIVE HARDNESS DATA

| Billet type | Reduction ratio | Extrusion temperature, °F | Preextrusion hardness, Rockwell C- | Postextrusion hardness, Rockwell C- |
|---|---|---|---|---|
| Hydrogen sintered, low-velocity extruded | 5.5:1 | 2300 | 31 | 45 |
| Vacuum arc-cast (a.c.), low-velocity extruded | 5.5:1 | 2300 | 33 | 49 |
| Vacuum arc-cast (d.c.), low-velocity extruded | 5.5:1 | 3100 | 28 to 30 | 41 |
| Vacuum sintered, high-velocity extruded | 9.5:1<br>16:1 | 3000<br>3500 | -------- | 27 to 30 |
| Vacuum arc-cast (d.c.), high-velocity extruded | 7.4:1<br>16:1 | 3000<br>3500 | 32 to 35 | 27 to 30 |

TABLE V. - TENSILE PROPERTIES OF EXTRUDED TUNGSTEN COMPARED WITH

COMMERCIALLY SINTERED AND SWAGED TUNGSTEN

| Billet | Reduction ratio | Extrusion temperature, °F | Test temperature, °F | Ultimate strength, psi | Approximate yield strength, psi | Reduction in area, percent | Total elongation, percent | Type of fracture (a) |
|---|---|---|---|---|---|---|---|---|
| Sintered and low-velocity extruded billets | | | | | | | | |
| S1 | 4.0:1 | 2300 | 1000 | 70,000 | 51,000 | 74 | 47 | Ductile |
| Vacuum-arc-cast (a.c.) and low-velocity extruded billets | | | | | | | | |
| A1 | 5.5:1 | 2300 | 1000 | 69,600 | ------ | 32 | 10 | Brittle |
| A2 | 5.5:1 | 2300 | 1000 | 68,600 | 62,000 | 63 | 27 | Ductile |
| Vacuum-arc-cast (d.c., reverse polarity) and low-velocity extruded billets | | | | | | | | |
| A3 | 5.5:1 | 3100 | 1000 | 70,000 | 62,000 | 62 | 27 | Ductile |
| A4 | 5.5:1 | 3100 | 700 | 77,600 | 70,000 | 24 | 12 | Brittle |
| A5 | 8.0:1 | 3100 | 1000 | 71,900 | 63,000 | 68 | 30 | Ductile |
| A6A | 5.5:1 | 3200 | 1000 | 61,900 | 58,000 | 63 | 28 | Ductile |
| A7A | 8.0:1 | 3200 | 1000 | 64,000 | 56,000 | 37 | 24 | Ductile |
| A7A | 8.0:1 | 3200 | 1000 | 61,000 | ------ | 63 | 23 | Ductile |
| A7A | 8.0:1 | 3200 | 1000 | 65,300 | 47,000 | 58 | 29 | Ductile |
| Vacuum-sintered and high-velocity extruded billets | | | | | | | | |
| SD1 | 16:1 | 3500 | 1000 | 35,900 | ------ | 2 | 3 | Brittle |
| SD5 | 9.5:1 | 3000 | 1000 | 40,700 | ------ | -- | -- | Brittle |
| Vacuum-arc-cast (d.c., reverse polarity) and high-velocity extruded billets | | | | | | | | |
| AD3 | 16:1 | 3500 | 1000 | 42,000 | ------ | 36 | 38 | Ductile |
| Sintered and swaged commercial rod stock | | | | | | | | |
| M1 | ----- | ---- | 1000 | 68,300 | ------ | 74 | 29 | Ductile |
| M2 | ----- | ---- | 1000 | 68,500 | 66,000 | 75 | 29 | Ductile |
| Vacuum-arc-cast (d.c., reverse polarity) and high-velocity extruded billet | | | | | | | | |
| A6A | 5.5:1 | 3200 | 4000 | 6,760 | ------ | 99 | 49 | Ductile |
| Sintered and swaged commercial rod stock | | | | | | | | |
| (b) | ------ | ---- | 4075 | 6,480 | ------ | 20 | 25 | Brittle |

[a]Brittle fracture, no necking; ductile fracture, specimen necked.

[b]Average of five tensile tests (ref. 8).

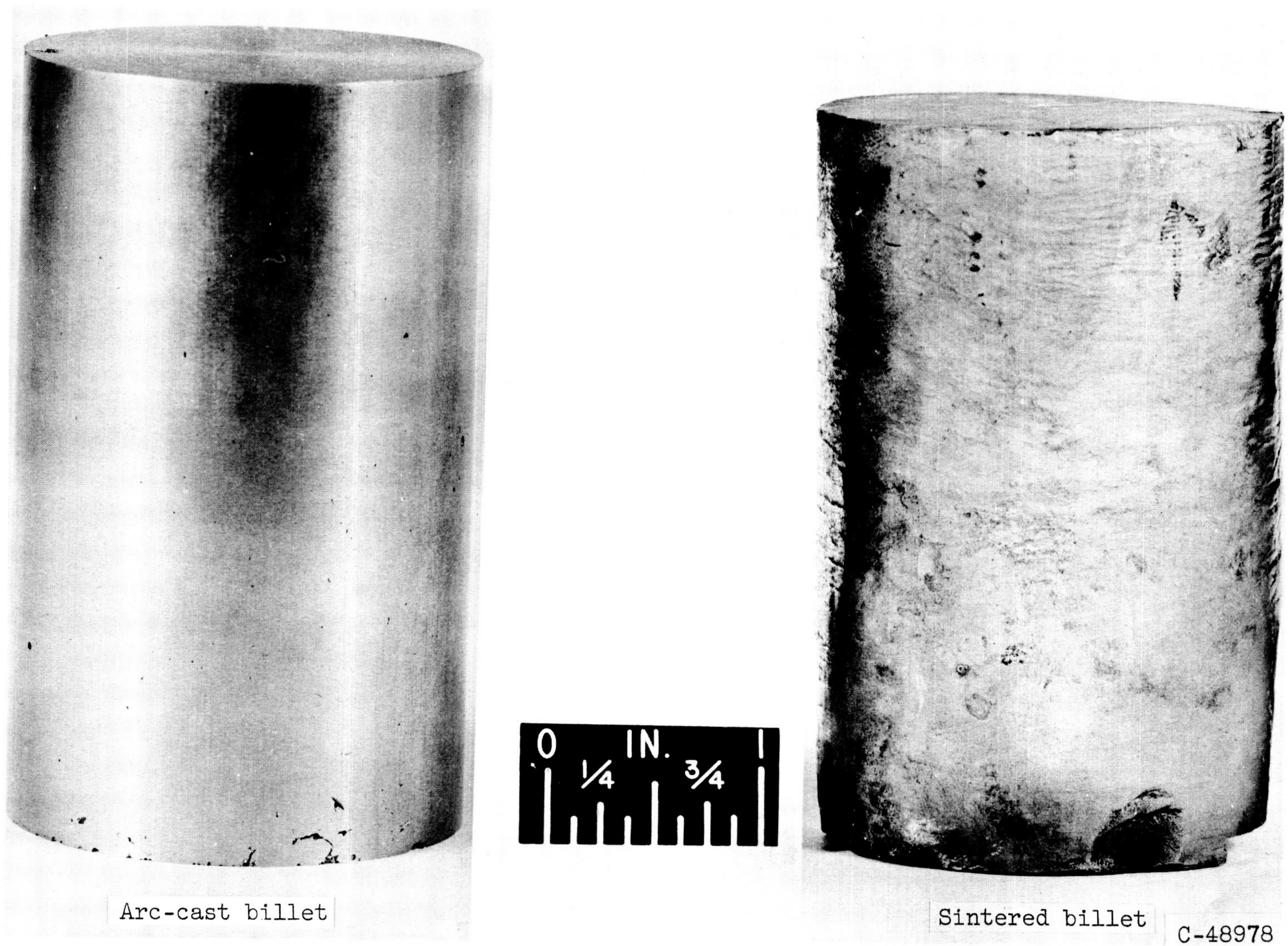



Figure 1. - Comparison of general appearance of arc-cast and sintered billets.

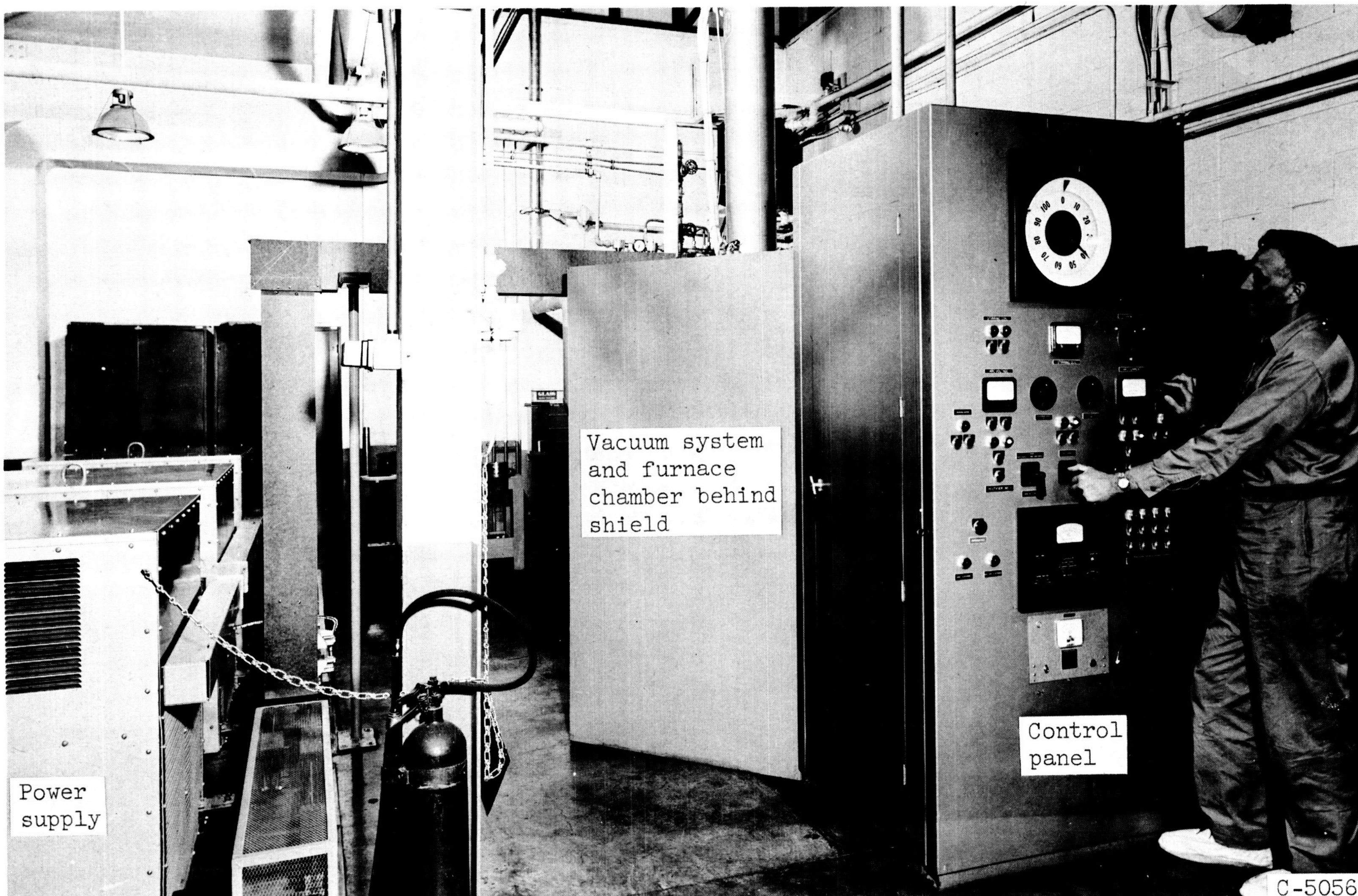



Figure 2. - Control panel and direct-current power supply of arc-melting furnace.

E-566

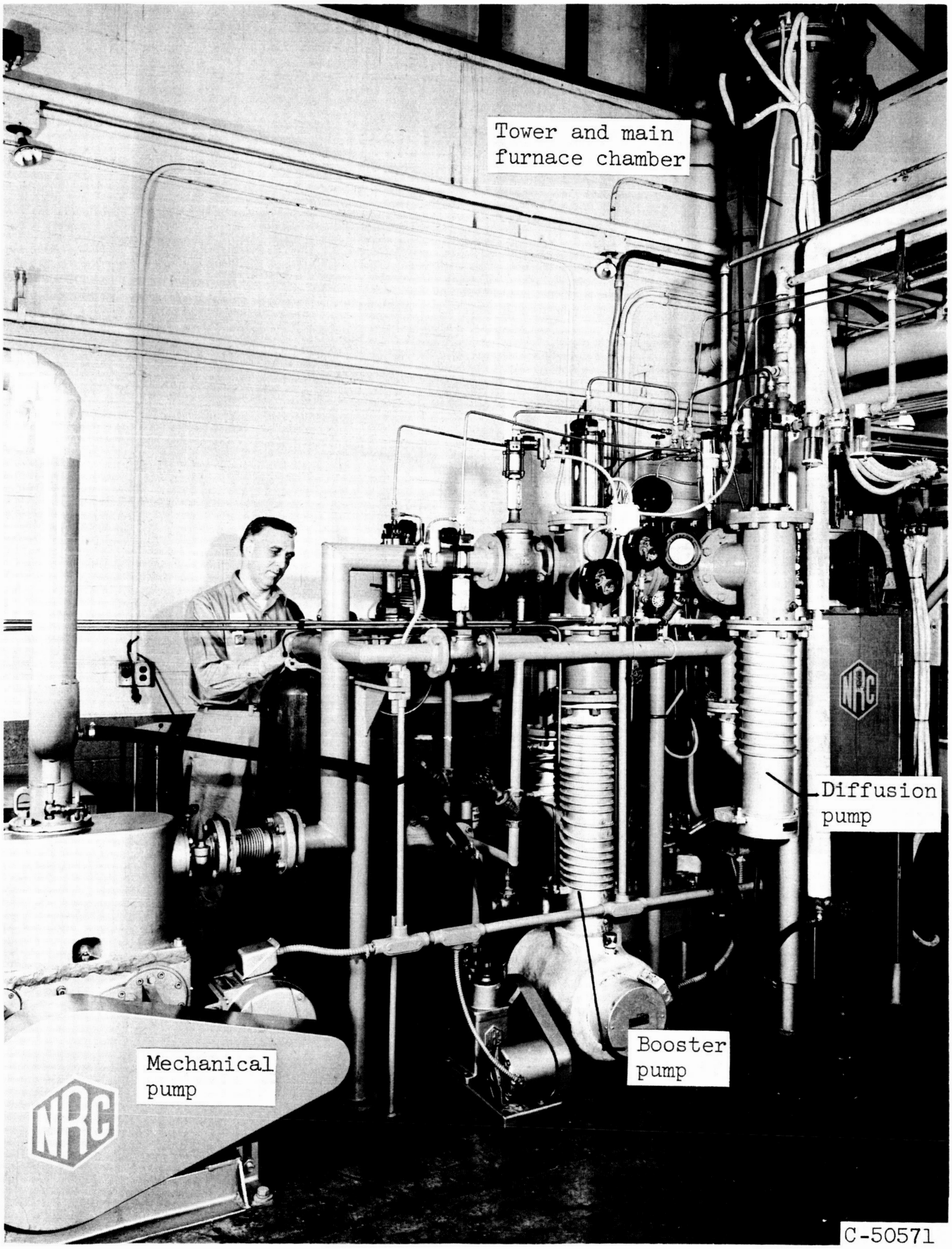



Figure 3. - Chamber and vacuum pumping equipment of arc-melting furnace.

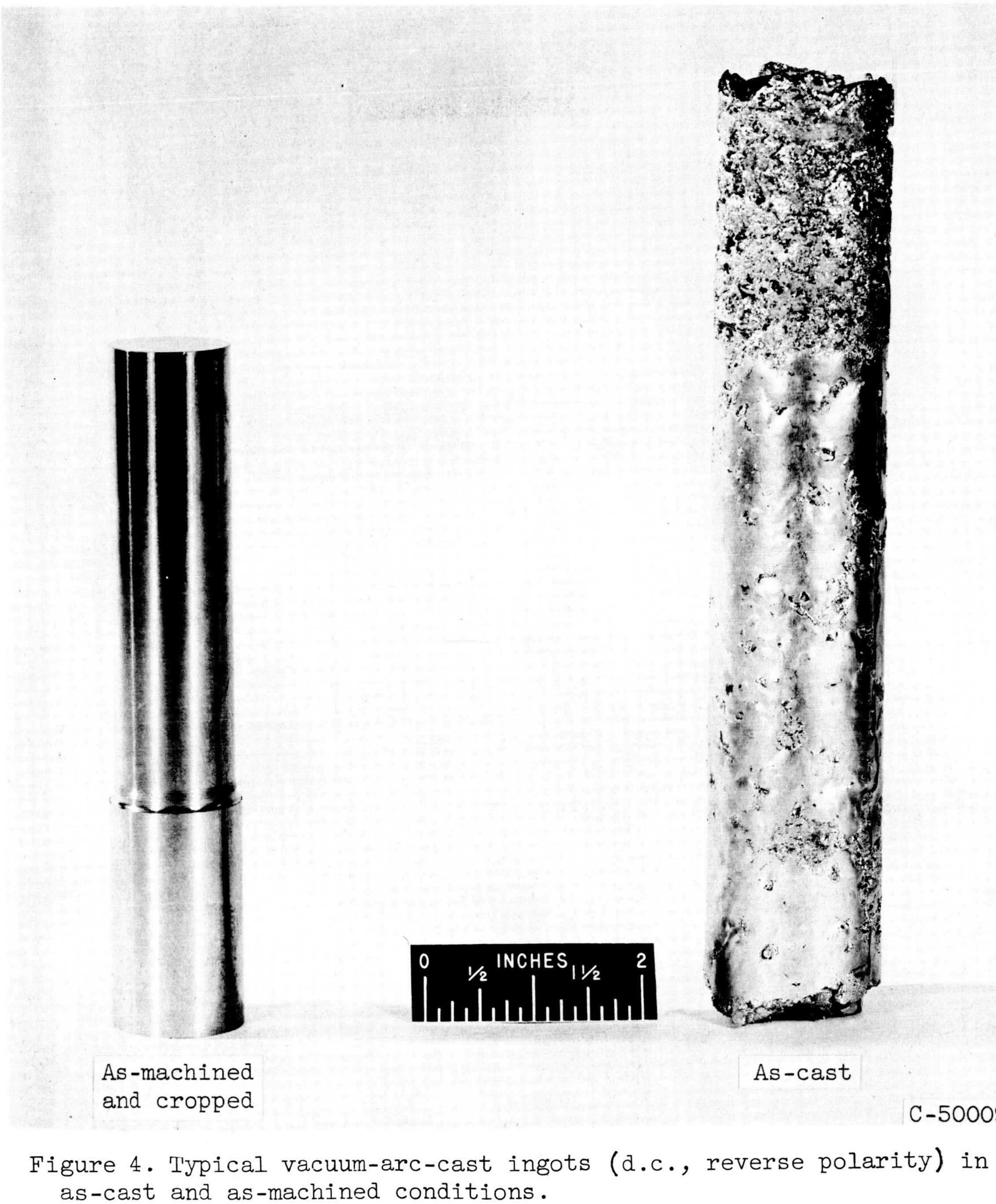



Figure 4. Typical vacuum-arc-cast ingots (d.c., reverse polarity) in as-cast and as-machined conditions.

E-566

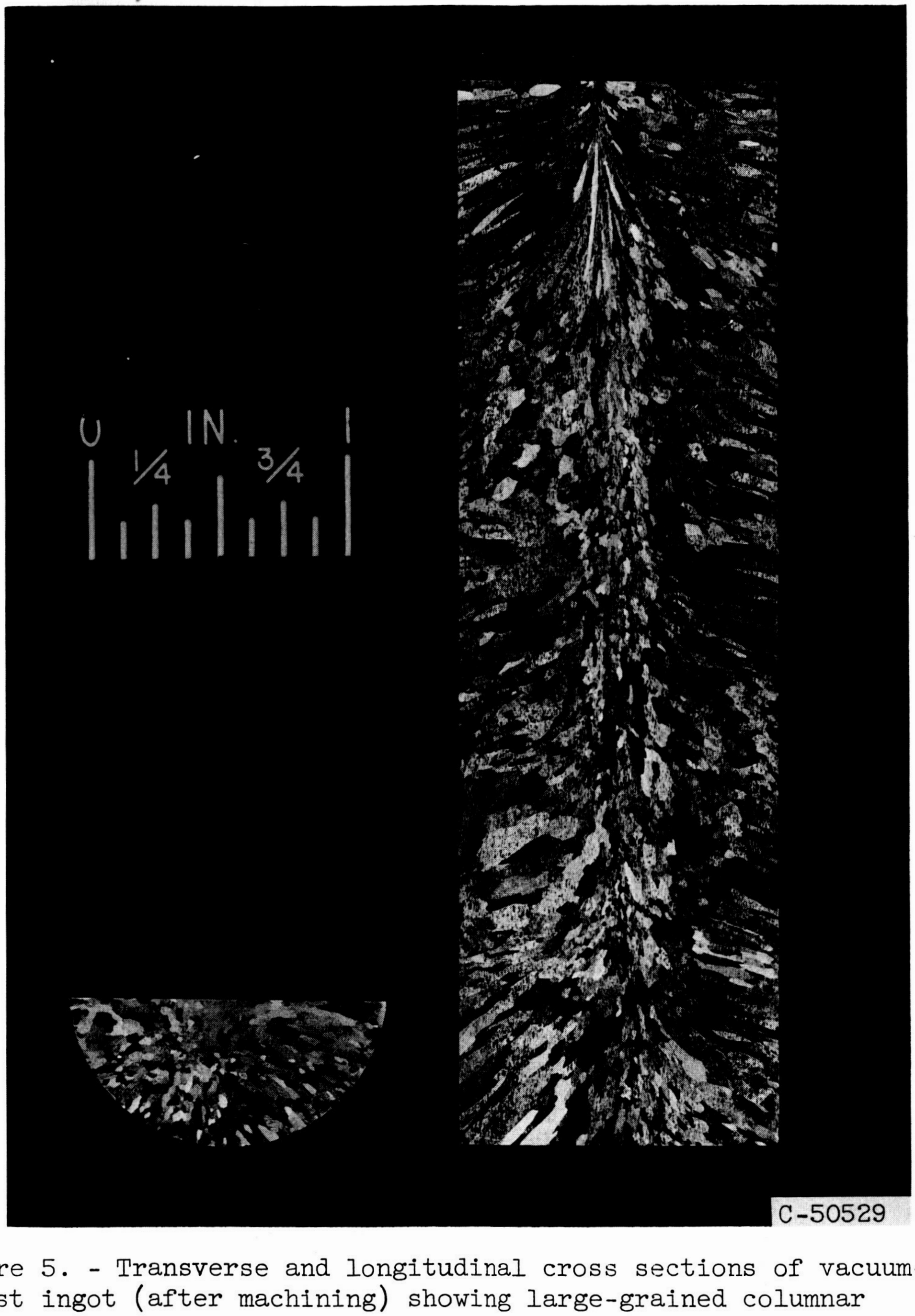



Figure 5. - Transverse and longitudinal cross sections of vacuum-arc-cast ingot (after machining) showing large-grained columnar structure.


C-48860

Figure 6. - Comparison of general appearance of stainless-steel-clad extruded arc-cast and sintered billets.


Figure 7. - Comparison of general appearance of extruded arc-cast and sintered tungsten after removal of stainless steel cladding. Spiral markings on extruded billets were caused by mechanical removal of cladding.

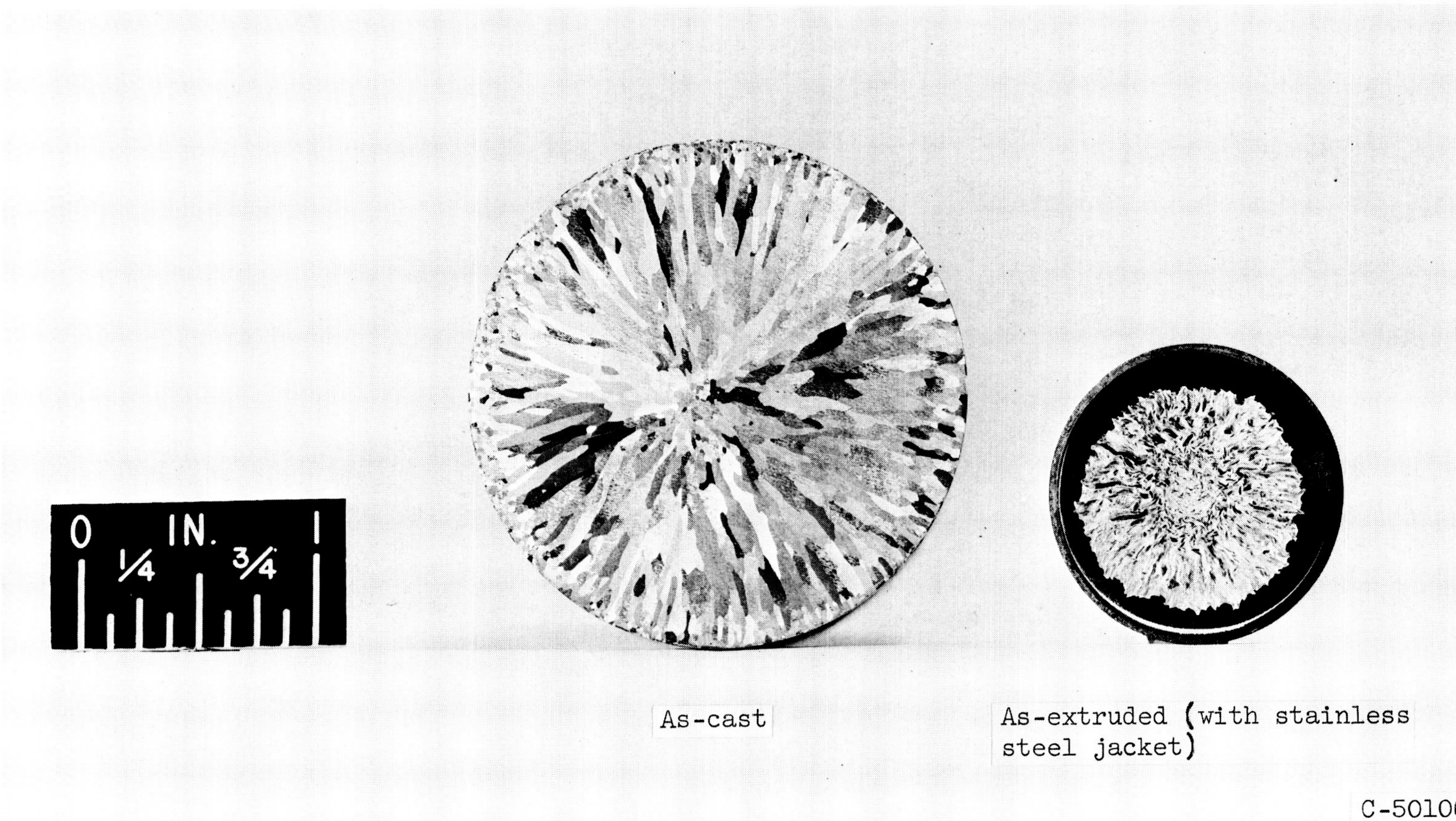
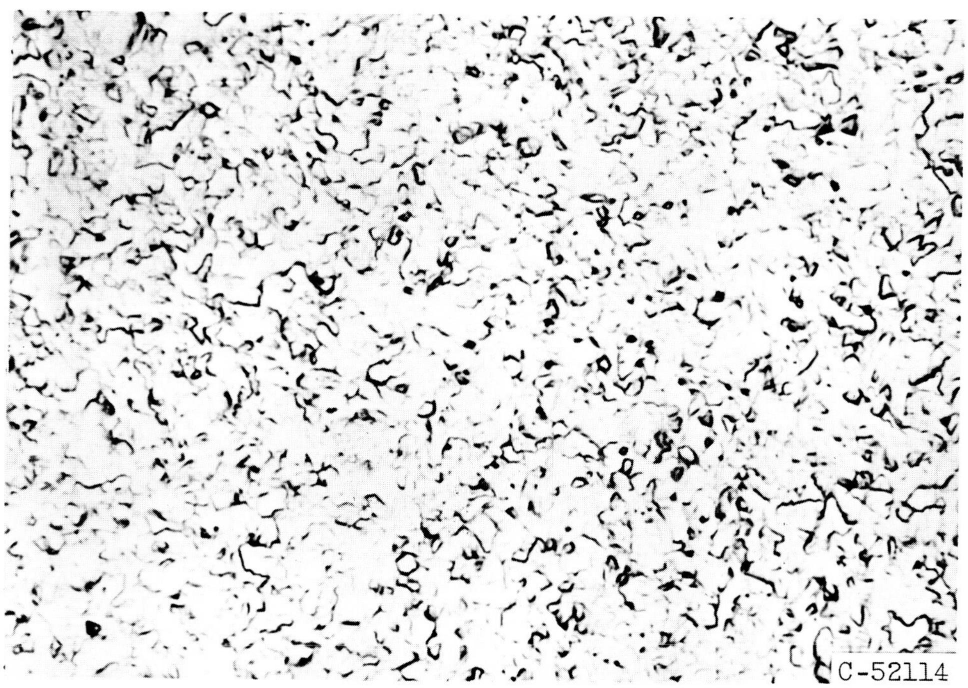



Figure 8. - Comparison of grain structure of vacuum-arc-cast tungsten in as-cast and as-extruded conditions.

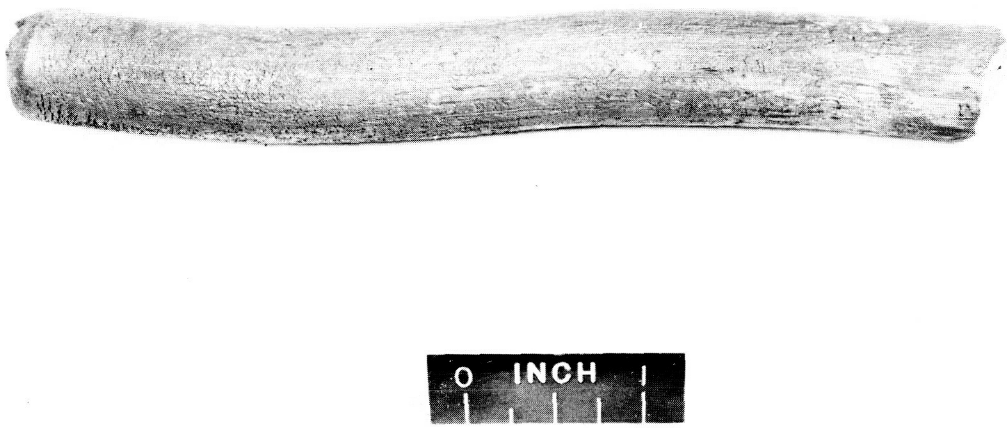
(a) As-sintered.




(b) As-extruded.

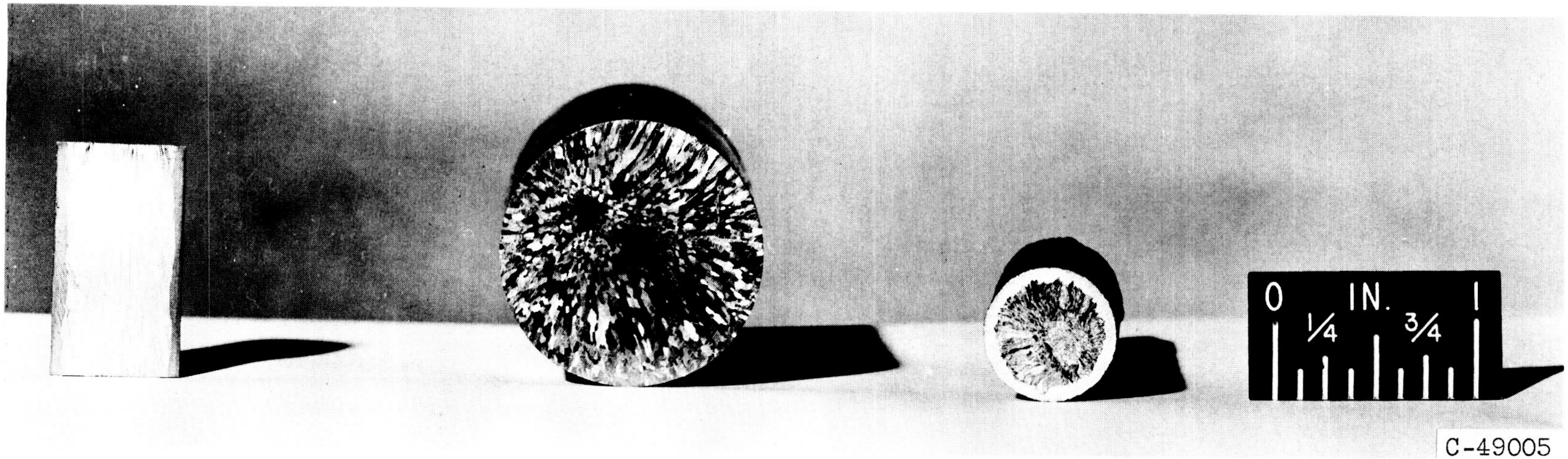
Figure 9. - Comparison of grain structure of sintered tungsten in as-sintered and as-extruded conditions. Cross-sectional views. X1000.

E-566




C-48857

Figure 10. - General appearance of portion of columbium-clad arc-cast tungsten extrusion.




Longitudinal section of columbium-clad low-velocity-extruded arc-cast billet.

Transverse section of arc-cast starting billet (with machined surface).

Transverse section of columbium-clad low-velocity-extruded arc-cast billet.

Figure 11. - Polished and etched sections of arc-cast starting billet and low-velocity-extruded billets with columbium cladding.

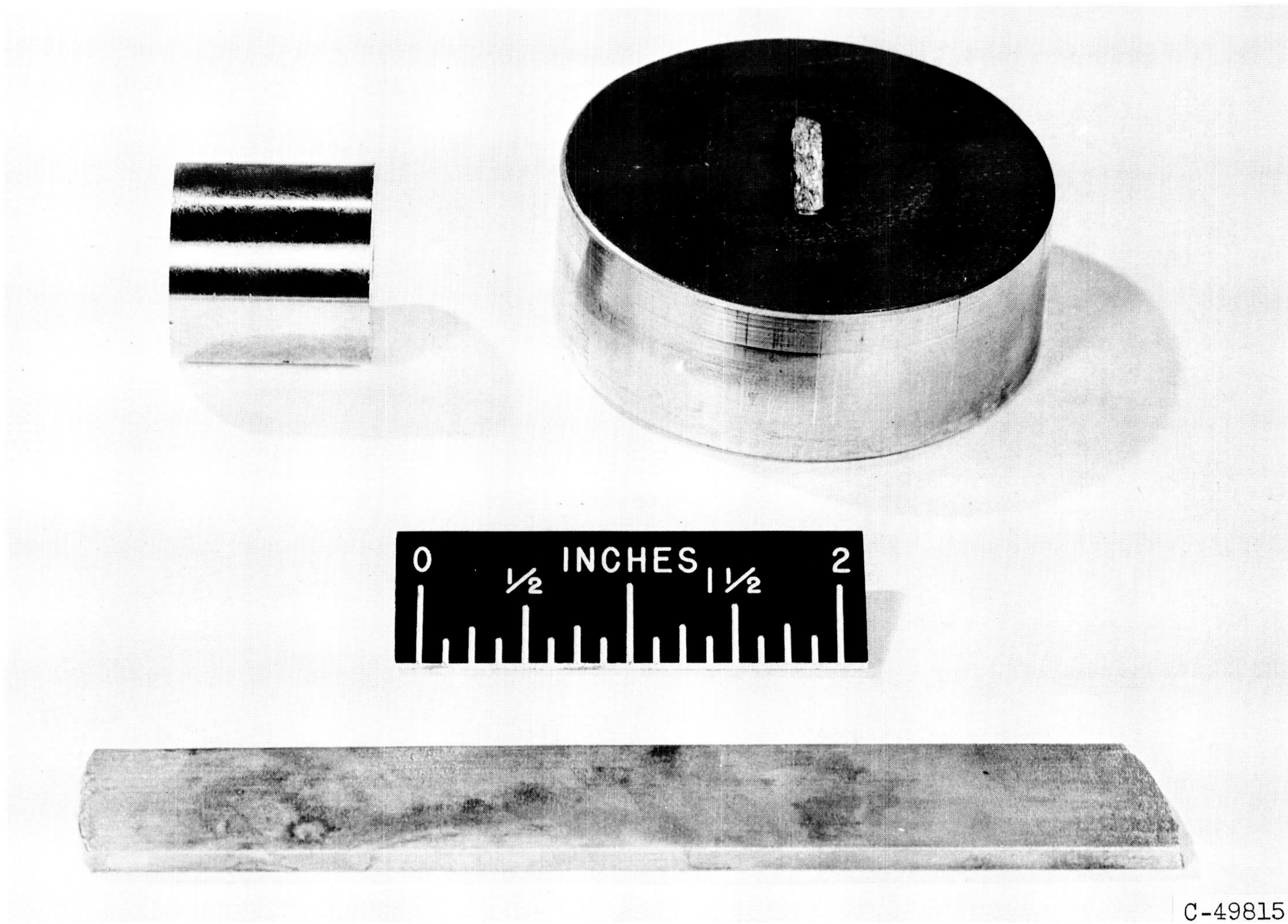



Figure 12. - Original arc-cast billet (AD4), die block, and high-velocity-extruded tungsten product with rectangular cross section. Reduction ratio, 8.3:1.

E-566

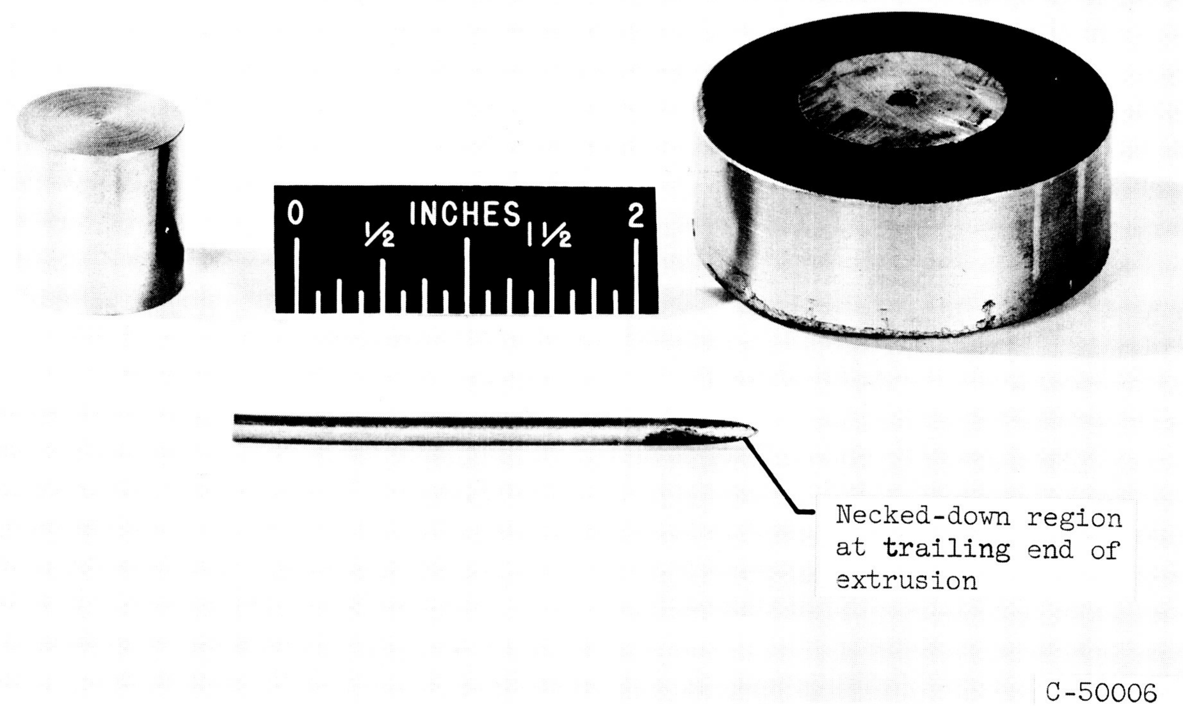



Figure 13. - Original arc-cast billet (AD5), die block, and high-velocity-extruded tungsten product. Reduction ratio, 40:1.

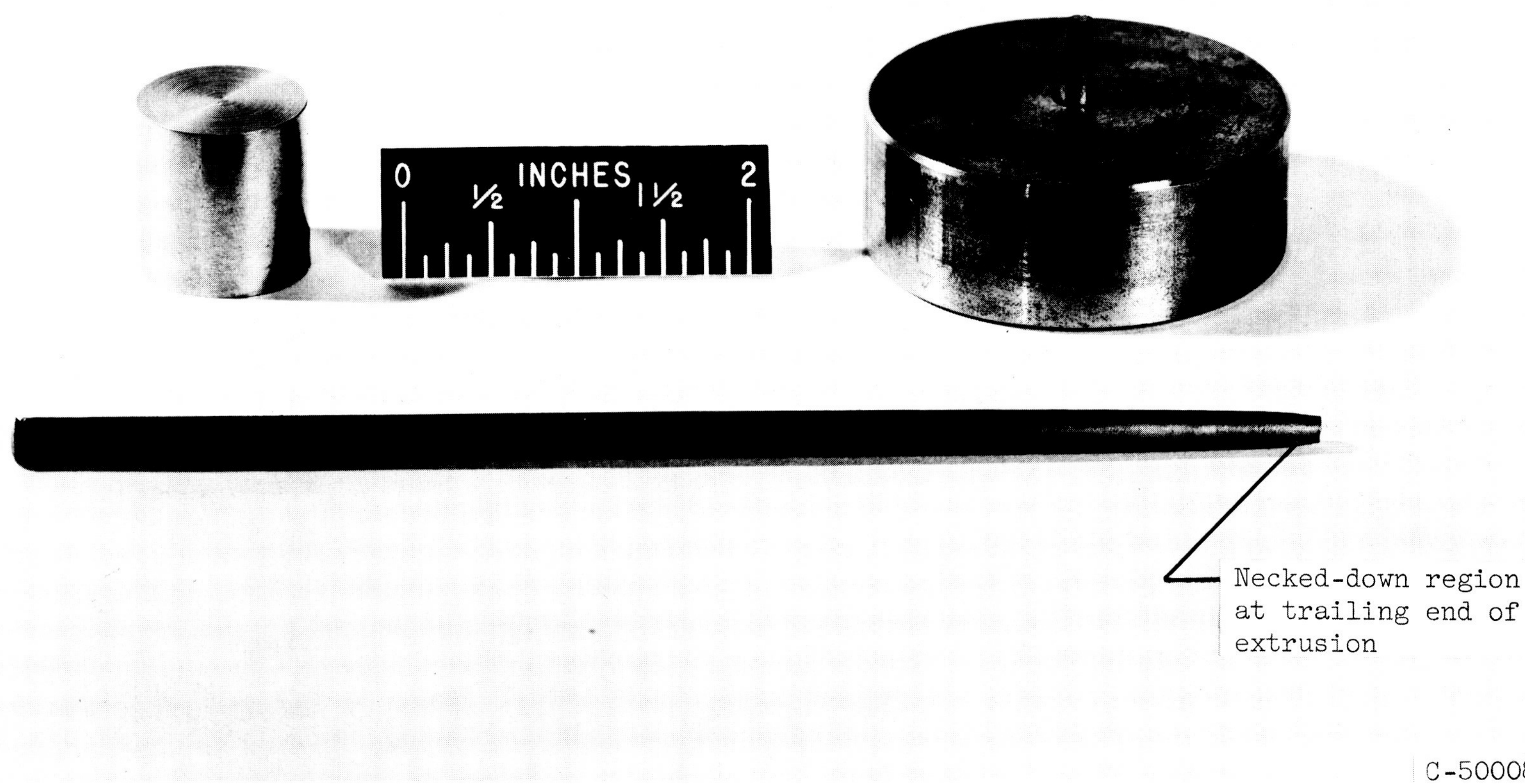



Figure 14. - Original sintered billet (SD1), die block, and high-velocity-extruded tungsten product. Reduction ratio, 16:1.

E-900

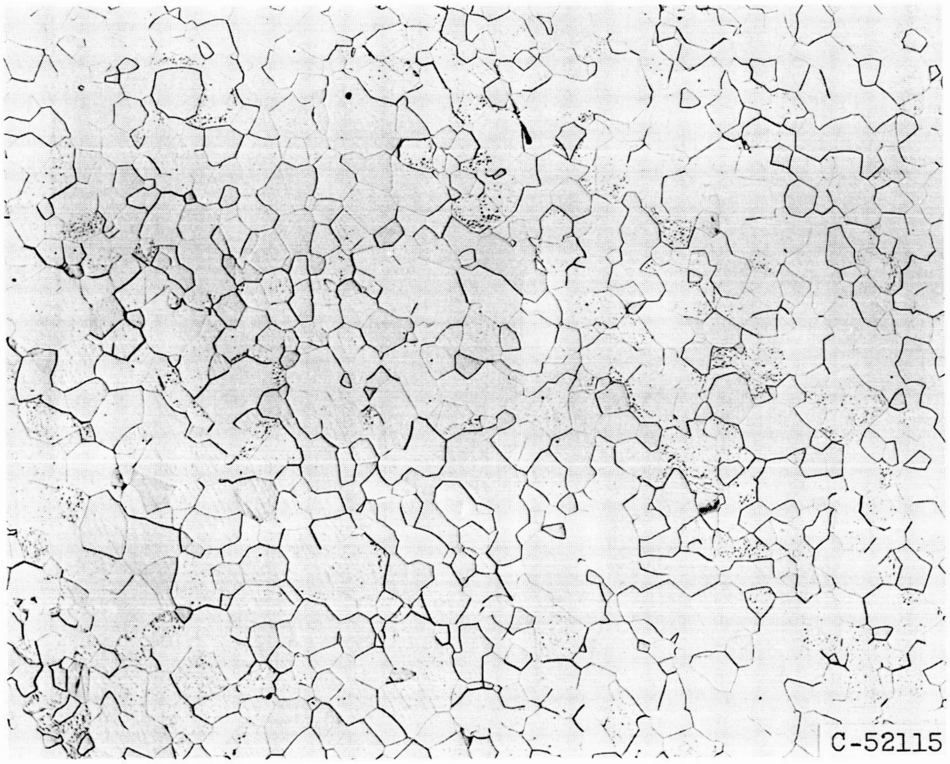



Figure 15. - Grain structure of arc-cast high-velocity-extruded tungsten. Longitudinal section. Reduction ratio at 3800° F, 45:1. X100.

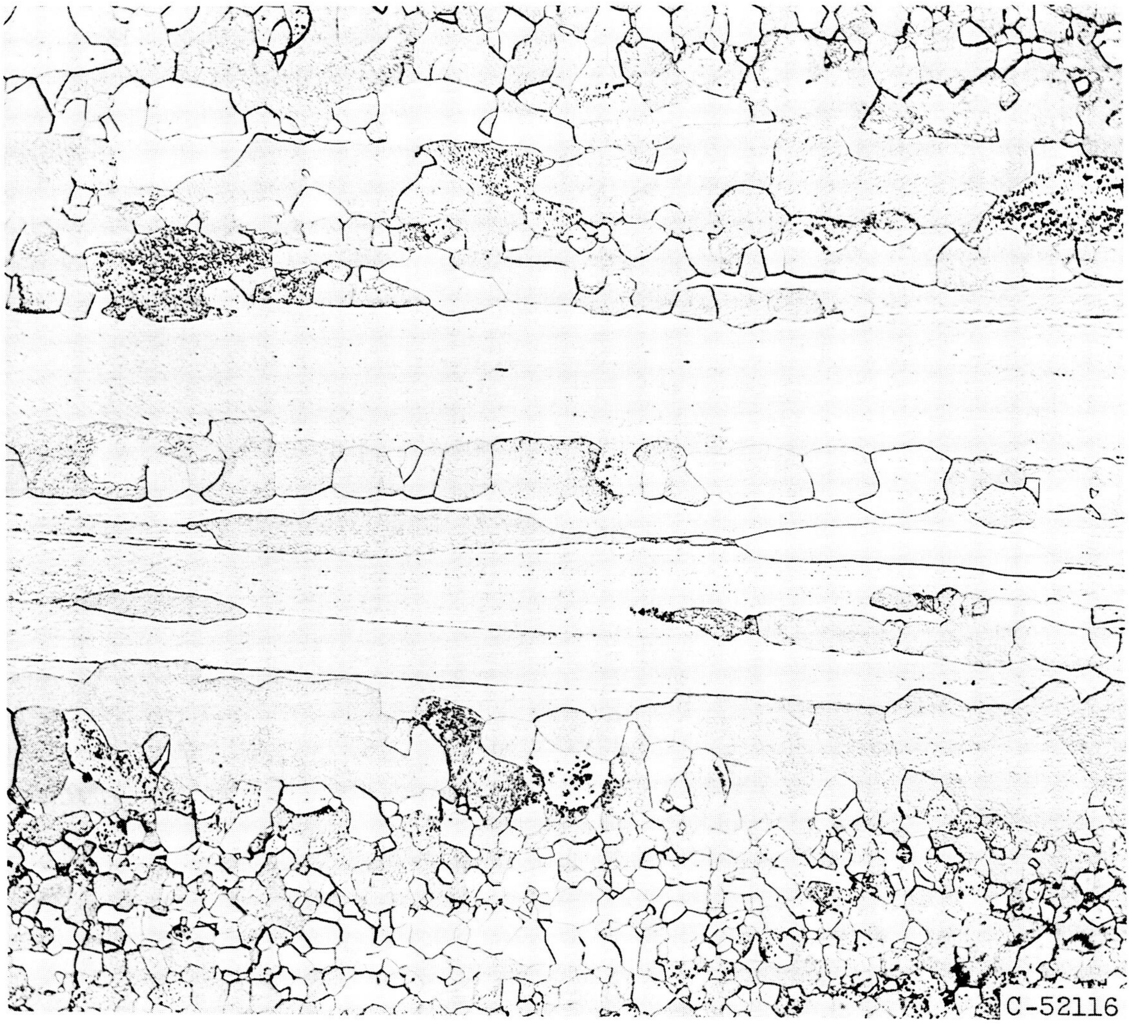



Figure 16. - Grain structure of longitudinal section of arc-cast high-velocity-extruded tungsten. Reduction ratio at 3000° F, 7.4:1. X100.

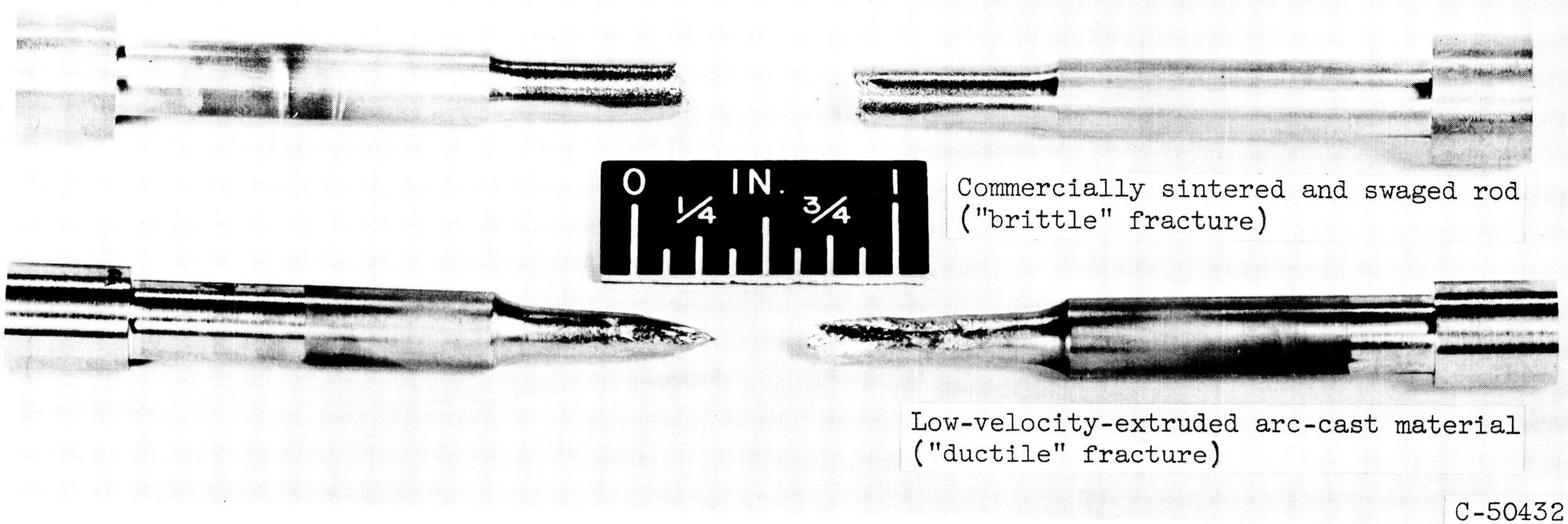



Figure 17. - Comparison of fractures of 4000° F tensile tests on processed tungsten.